A Silicon Tracker for the Linear Collider
(An Evolving Design)

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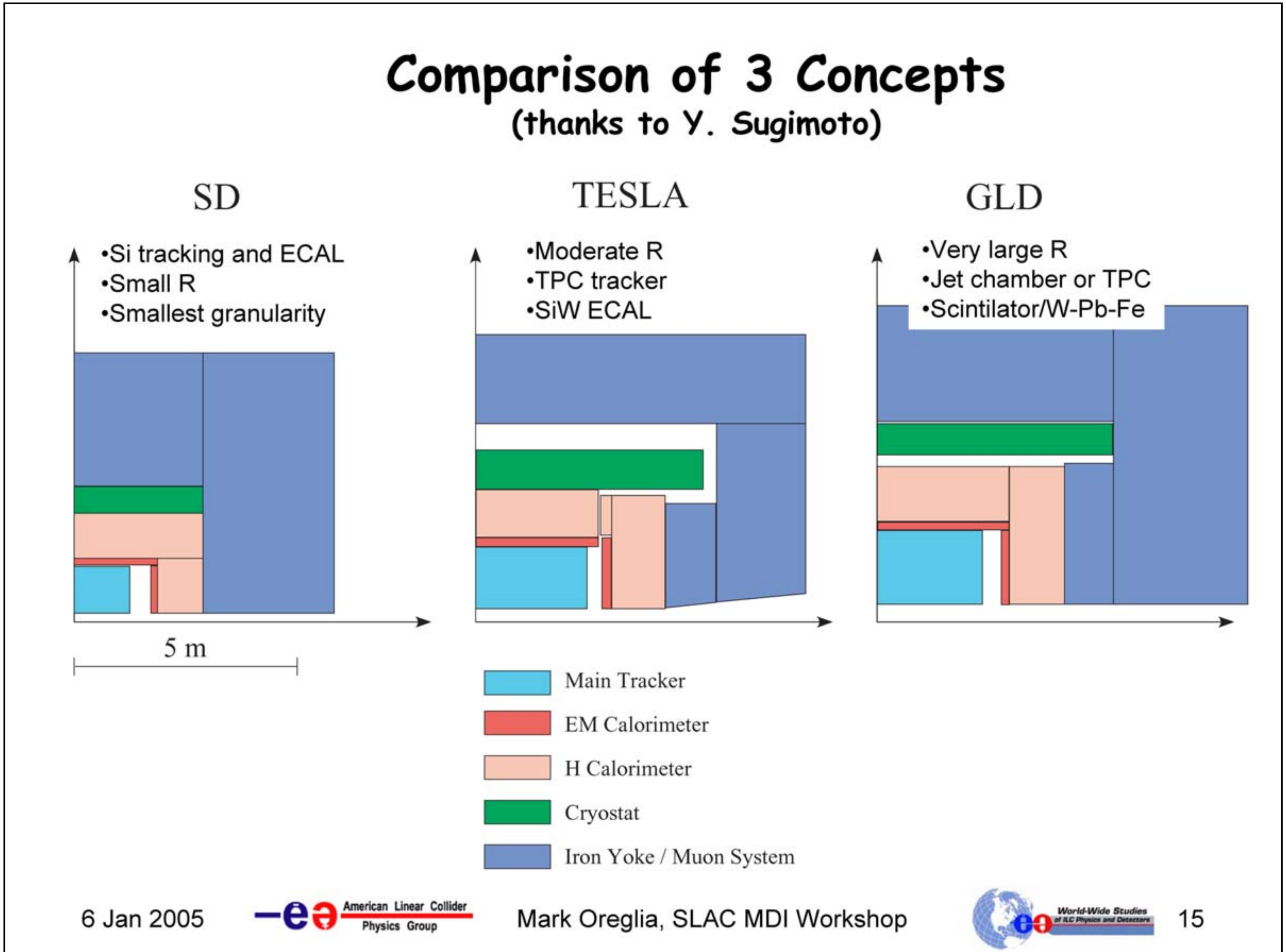
Three Overall Detector Options Described in the SLAC Machine Detector Interface Workshop



SiD Design

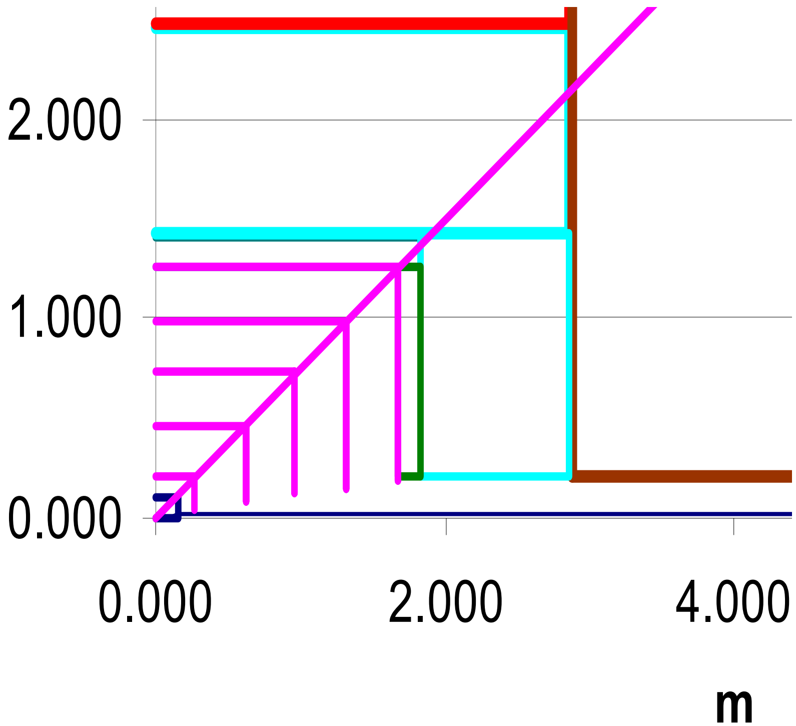
- SLAC / FNAL design effort led by J. Jaros, H. Weerts
- Choices of design parameters have been guided by a spreadsheet from M. Breidenbach
- Based upon an all-silicon tracker and controlling costs, that led to the highest B field and lowest solenoid diameter of the three options.
  - $B \approx 5$ T
  - Solenoid (IR, OR, L) ≈ (2.5 m, 3.3 m, 6.5 m)
- A silicon pixel vertex chamber within the tracker is assumed in all designs.
- For the SiD design $\delta Pt/Pt^2 \approx 3.6 \times 10^{-5}$

  (to be compared with 1.5×10^{-4}, 1.2×10^{-4} for the other designs)
- SiD employs a tungsten – silicon ECAL
  - A slightly simpler version of the chip being developed for ECAL readout might be used in the silicon tracker.
  - Then significant portions of the ECAL and silicon readout chains could be identical.

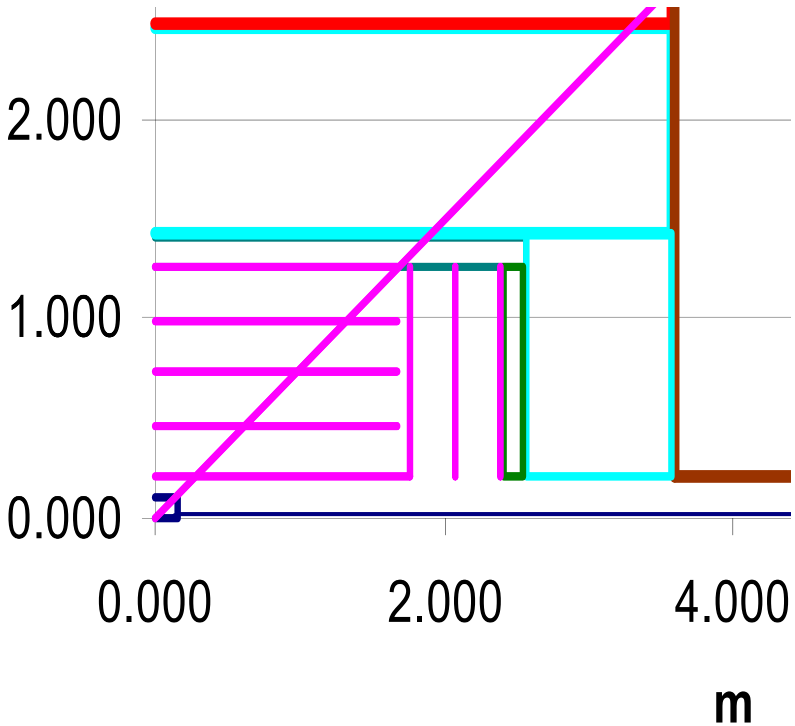
SiD Design

- For SiD, two general tracker geometries have been considered.

Barrels of stepped lengths
Inset disks



Barrels of a single length
Disks at ends

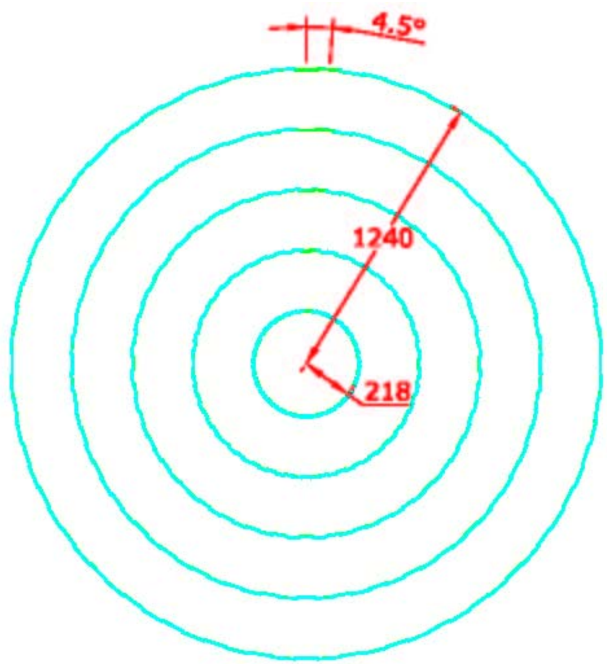


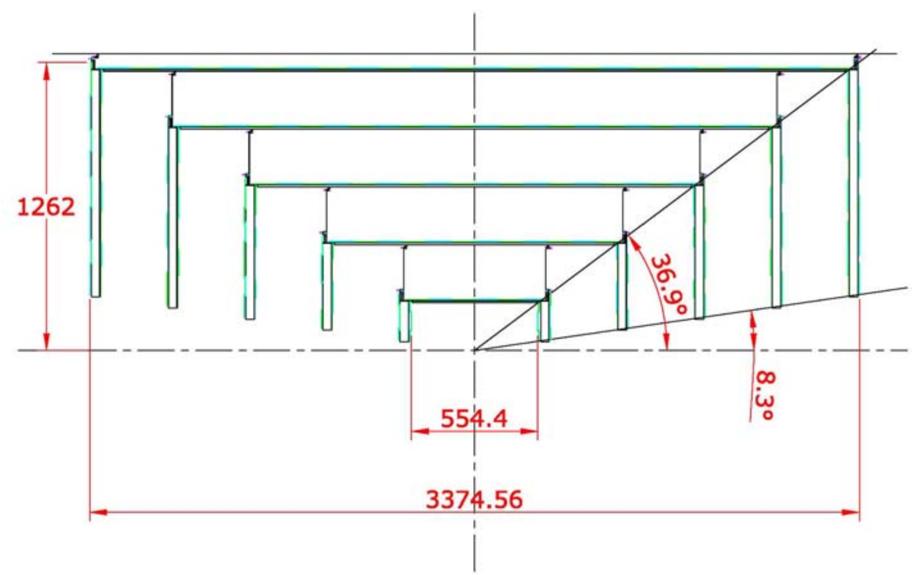
- Initially, we have concentrated on the left of the two geometries. The geometry to the right is not excluded, nor is an intermediate approach.

Overall Geometry for the Design Presented in Victoria

- Barrels
  - Five barrels
  - Measure Phi only
  - Eighty-fold phi segmentation
  - Barrel lengths increase with radius
  - Maximum active radius = 1.240 m
  - Minimum active radius = 0.218 m
  - Maximum active length = 3.307 m

- Disks
  - Five double-disks per end
  - Measure R and Phi
  - Disk radii increase with Z
  - Maximum active radius = 1.262 m
  - Minimum active radius = 0.041 m
  - Maximum Z (active) = 1.687 m
  - Minimum Z (active) = 0.282 m



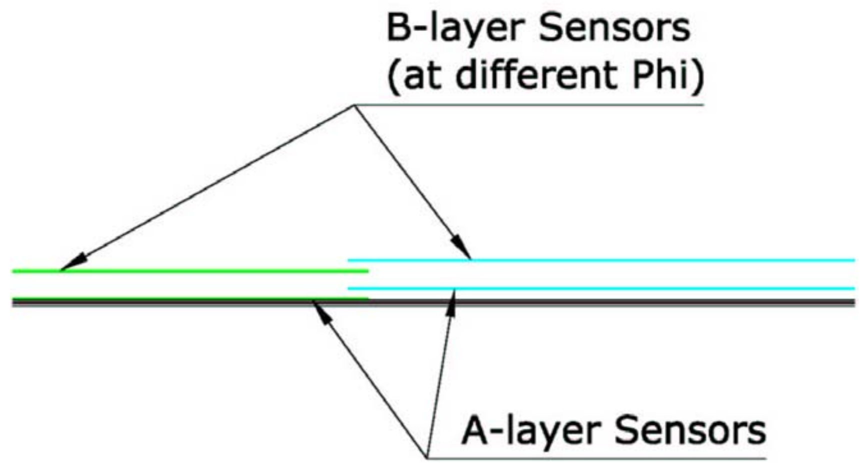


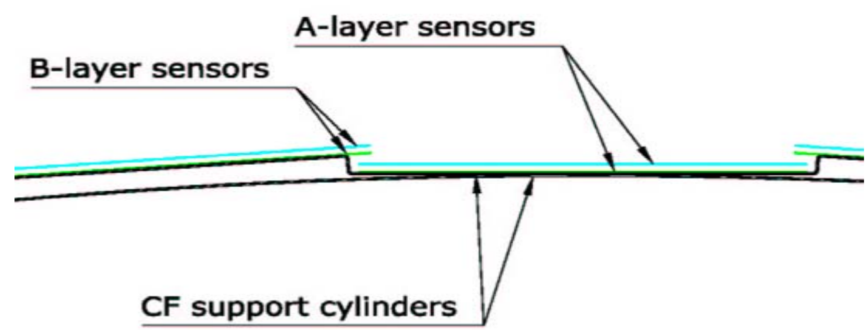
Participants

- Development of the design for Victoria
  - Cooper, Demarteau, Hrycyk
- Engineering for that design since Victoria
  - Krempetz, Ang Lee
- Others participating in local meetings at SiDet, Wednesdays, 8:30 – 10:00 AM
  - Weerts, Onoprienko, Partridge, Von Toerne
  - If interested, send email to cooper@fnal.gov or demarteau@fnal.gov
- Other participants in local silicon activities
  - Savoy-Navarro, Schumm, Tkaczyk, Fisk, Milstene
- Coordination with the larger SiD group
  - Weekly telephone conference on Fridays 11:00 AM – 12:30 PM
  - Local participation from the SiDet conference room
  - http://www-sid.slac.stanford.edu/
  - Listserver: sid-tracking@fnal.gov
- Fermilab ILC web page
  - http://ilc.fnal.gov/
- Harry Weerts is organizing a Detector – Machine Interface Meeting
  - First meeting January 19, 9:30 AM. Room to be arranged.

Barrel Features

- 100% overlap of sensor active regions is provided in both Z and phi.
  - Adjoining sensors in Z are offset radially by ~ 1.9 mm.
  - Adjoining sensors in phi are offset radially by ~ 5 mm.
  - Full efficiency of the innermost barrel is needed for good track-matching from the vertex chamber.
- Double-walled, CF-based support cylinders are shown.
  - Separation of inner and outer walls (probably ~12 mm) is set by the required out-of-round stiffness and provided via Rohacell spacers.
  - As a practical matter, the outer cylinder would probably be an 80-sided polygon with radial positions of A- and B-layers set via supports for module sub-assemblies.
  - The inner wall could be circular and would be cut shorter than the outer to allow space for disks and mechanical connections.





Barrel Sensors in the Victoria Design

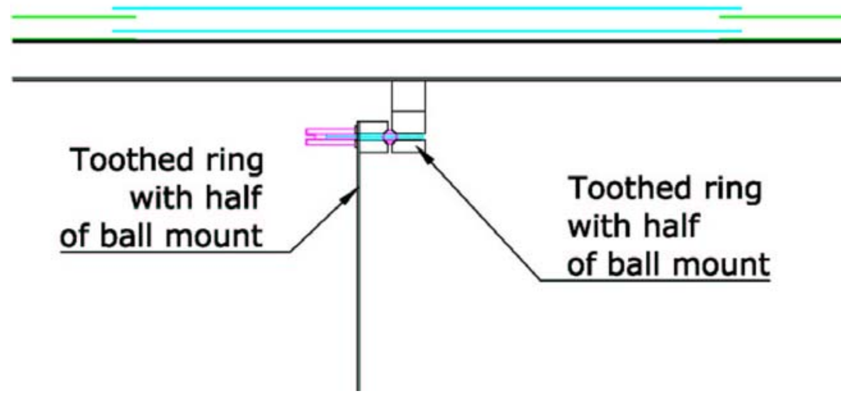
- Five types of sensors with a single type per layer
- All sensors are assumed to be single-sided and to have traces parallel to the beam line.
  - Could add stereo layers by widening and rotating sensors
- Sensor design is straight-forward and conventional.
  - Pitches of 50 μm and 51 μm
    - Could be varied without complications
  - Sensors could have intermediate strips.
  - Sensor cut lengths:
    - 103.6, 110.2, 112.4, 113.5, and 141.7 mm
  - Sensor cut widths:
    - 21.2, 40.4, 59.6, 80.4, and 100.0 mm
  - Barrel 1 through 3 sensors fit within 6” wafers.
  - Barrel 4 and 5 sensors require 8” wafers.
- Azimuthal segmentation of the smaller radius barrels may need to be reconsidered.
  - A common readout chip design argues for a reduction in the number of sensor widths.

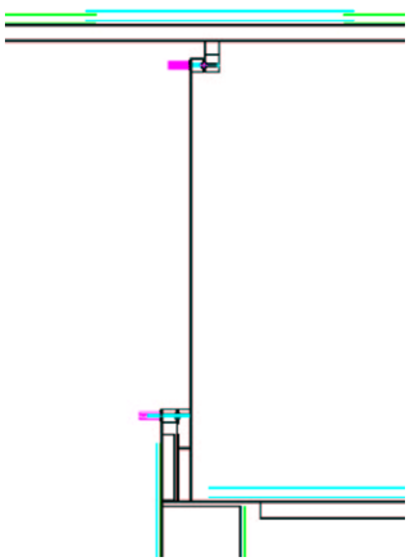
Disk Features

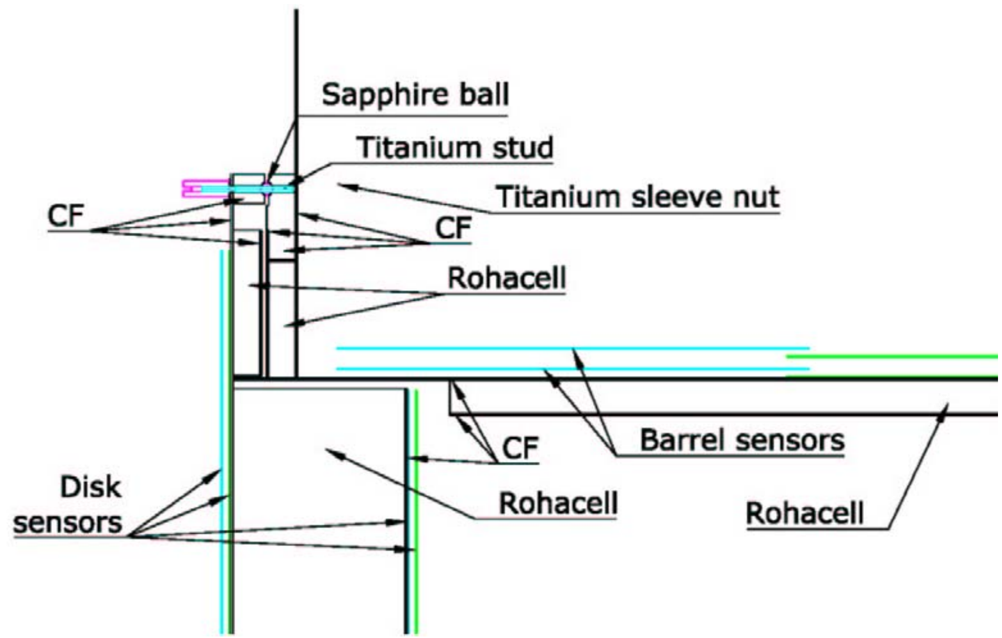
- We followed the same general assumptions as were applied to the barrels:
  - ~ 1.0 mm overlap between sensor active regions
  - 1.02 mm wide border for guard rings.
- Sensors are on opposite surfaces of CF – Rohacell support structures.
- Adjacent sensors are positioned at slightly different Z’s to provide R and Phi overlap.
- A-surface sensors fit a short distance within an associated barrel and are supported via a CF – Rohacell – CF sandwich from CF of the B-surface.
- B-surface sensors cover the end of an associated barrel. A mechanical connection is made from the CF of the B-surface to the end of the barrel.

Connections among Barrel and Disk Assemblies

- Disk to barrel connections are critical in this design. One end is shown.
  - At the other end, the stud is attached to the disk in order to allow the connection to be completed. Barrels are clocked during installation to allow teeth to pass one another.

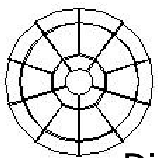




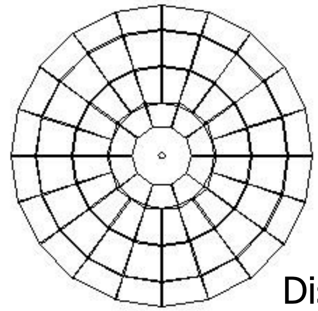


Disk Geometries

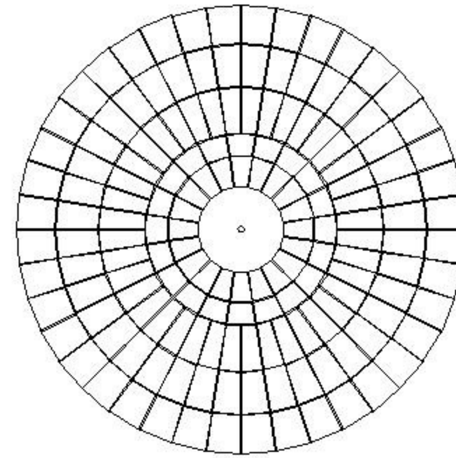
- All are shown with approximately the same relative scale



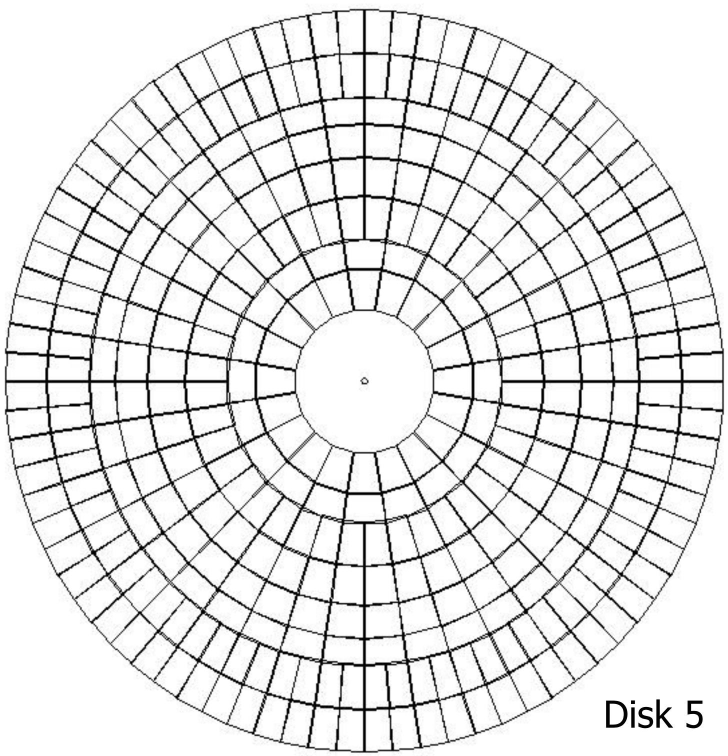
Disk 1



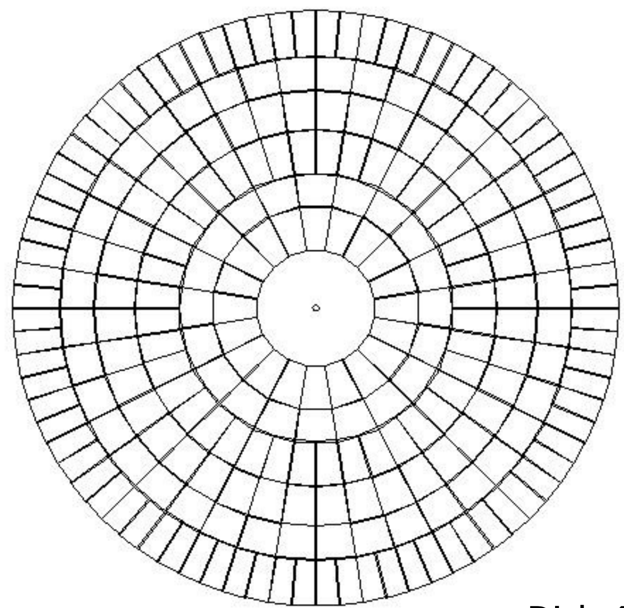
Disk 2



Disk 3



Disk 5

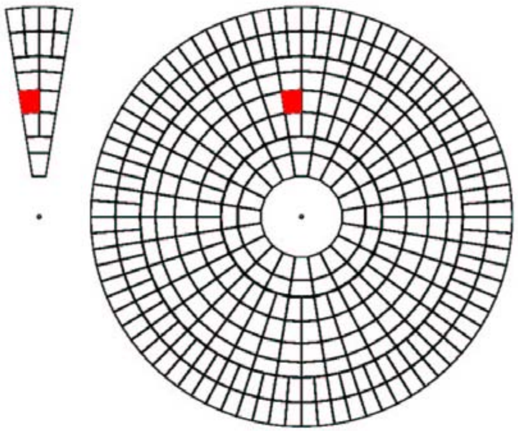


Disk 4

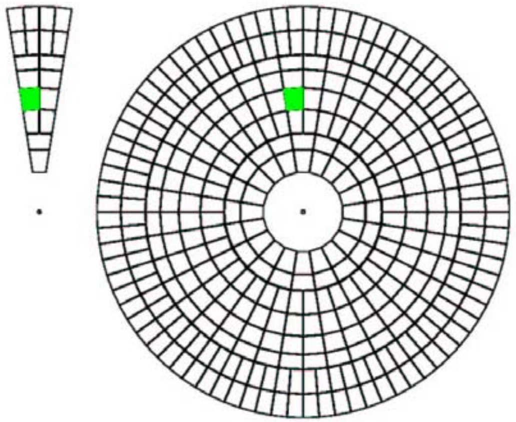
Disk Layouts

- Wedge cut, rather than active, edges were aligned at a constant phi.
  - That allows alignment of wedges using cut edges, a significant simplification during assembly.
  - For a constant overlap distance, traces do not quite point towards the beam line.
- The eighty-fold symmetry at the outer disk radius (disk 5) matches that of barrels.
- To maintain sensible trace lengths, the phi multiplicity with which sensors are arrayed has been decreased as one moves to smaller radius: 80, 40, 20-fold in disk 5 and as low as 10, 5-fold in disks closer to Z = 0.

Disk 5B, Y sensors



Disk 5A, Phi sensors



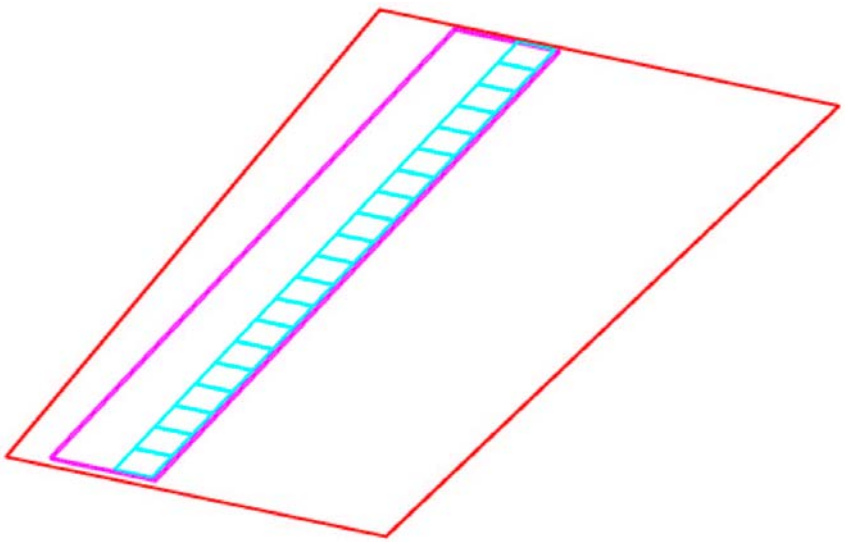
Figures by Mike Hyrcyk

Disk Layouts

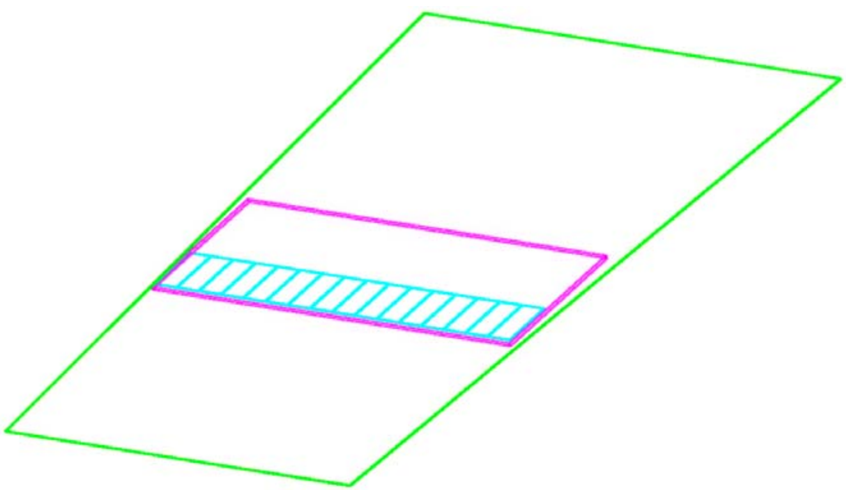
- In the Y sensors, traces run parallel to the inner wedge edge and have constant pitch.
- Trace lengths vary.
- Hybrids have readout chips arrayed parallel to Y.
- Transverse position of the hybrid is arbitrary within reasonable limits.
- More recent thinking is that only about 25 mm^2 would be needed for a 1024 channel chip.
- An additional sensor metal layer would carry trace connections to the chip.

- In the Phi sensors, trace ends are evenly spaced laterally at inner and outer edges. The pitch increases linearly with Y.
- Variations in trace length are modest.
- Hybrids have readout chips arrayed parallel to the inner wedge edge.
- Y position of the hybrid is adjusted to match chip pitch to sensor pitch.

Disk 5B, Y sensor 4

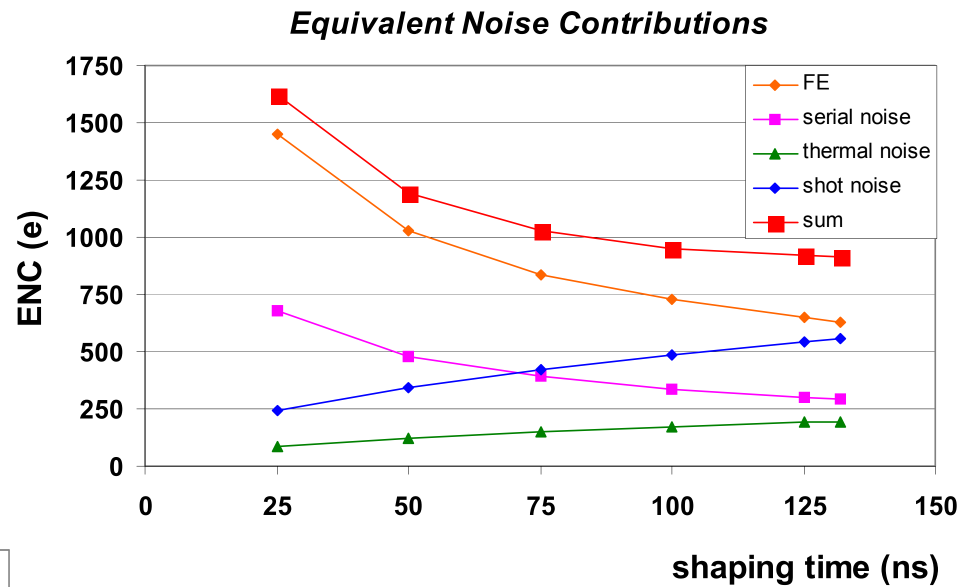


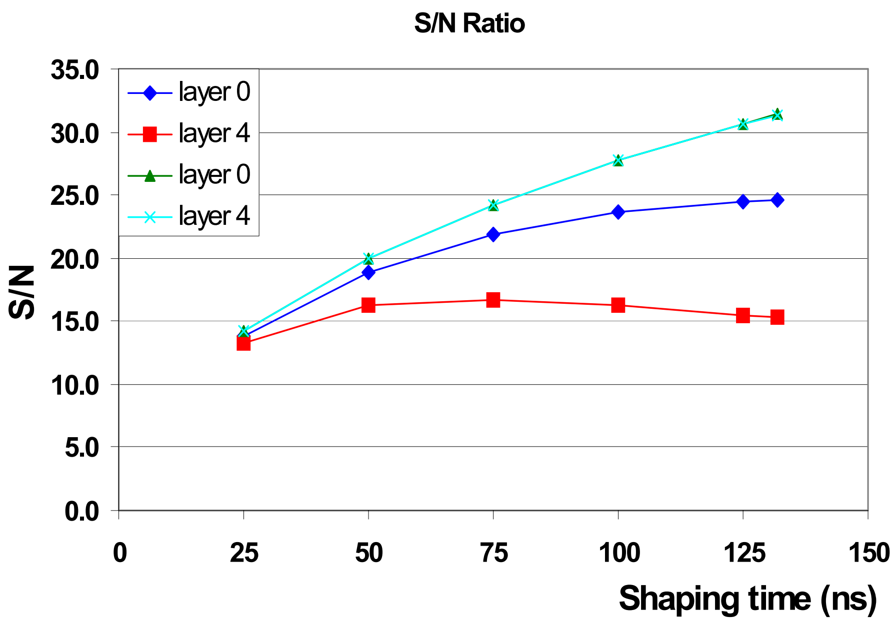
Disk 5A, Phi sensor 4



Noise Performance Based Upon SVX-4 Chips

- Calculations by Marcel Demarteau for the Victoria Workshop
- S/N:
  - innermost and outermost layer
  - Two temperatures: T=20° C and T= -10° C





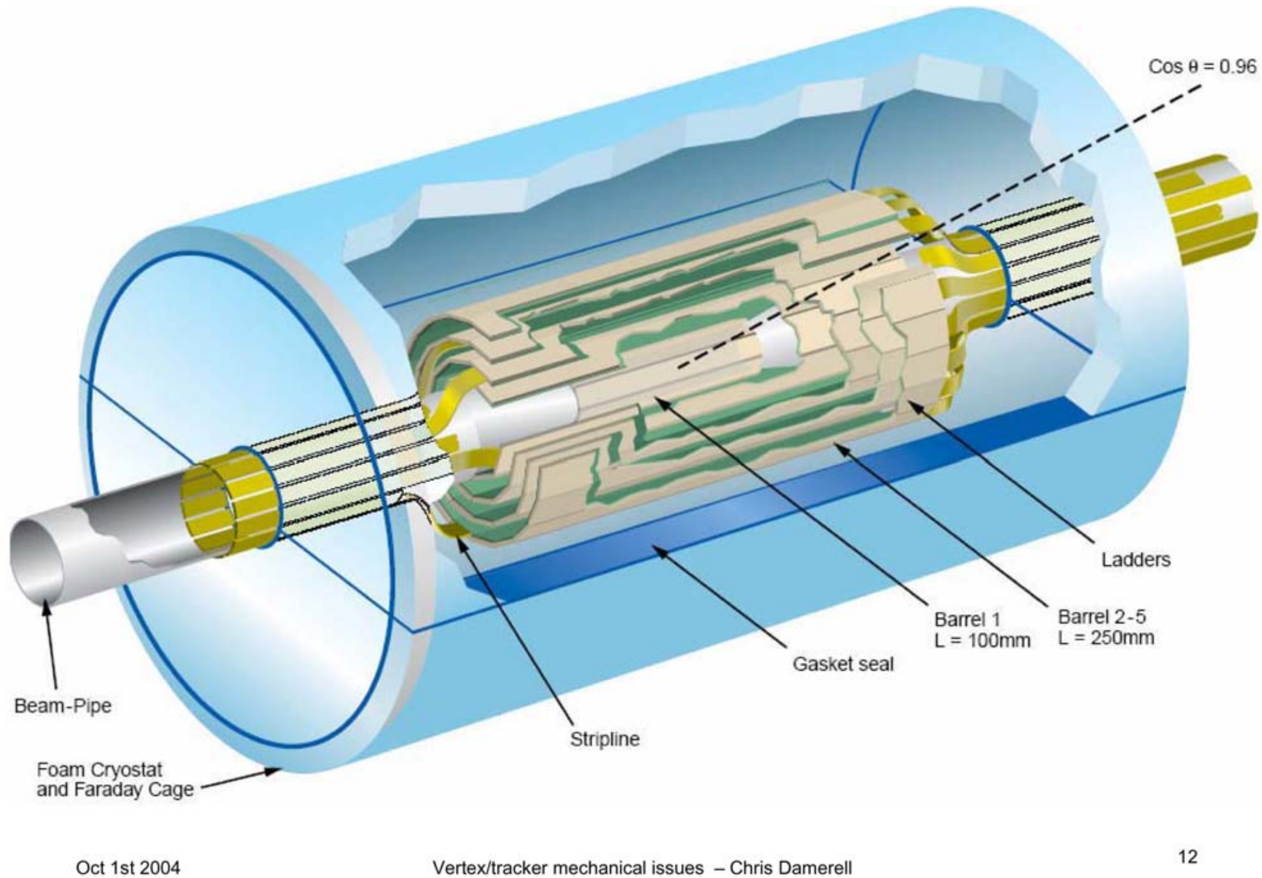
Sensor and Chip Counts

Barrels (Layer)	Sensors	Active area (m^2)	Chips	Disks (Sum of two ends)	Sensors	Active area (m^2)	Chips
1	640	1.72	1920	1Phi + 1R	100	0.70	1140
2	960	4.11	5760	2Phi + 2R	280	2.93	4240
3	1440	9.15	12960	3Phi + 3R	640	6.75	9600
4	1920	16.26	23040	4Phi + 4R	960	12.17	16160
5	1920	19.50	28800	5Phi + 5R	1440	19.16	23840
Sum	6880	50.73	72480	Sum	3420	41.71	54980
Barrels + both sets of end disks					10300	92.44	127460

- Chip counts, based upon 128 channels per chip, are high.
  - That is consistent with a pitches of 50 - 60 μm, trace lengths of 100 – 140 mm, and no ganging of sensors.
- Chips with 1024 channels are being designed.
  - That impacts azimuthal segmentation, particularly for the barrels at smaller radius.
- Air cooling is assumed.
  - For 290 watts removed (consistent with air cooling), that corresponds to 18 μwatts per channel → power cycling.

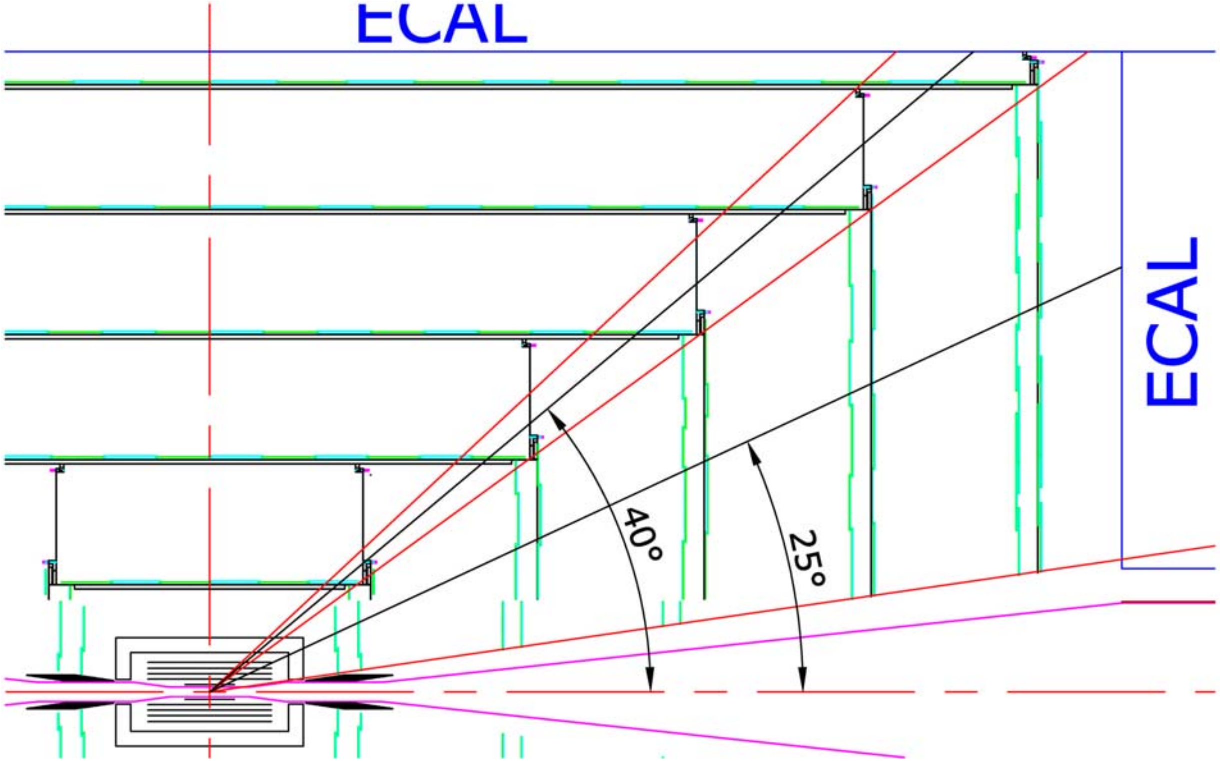
Vertex Chamber (Chris Damerell)

- Based upon silicon pixels
- The vertex chamber is supported from the beam tube assembly.
- The beryllium shell which surrounds the pixel detector transmits moments from the left beam pipe portion to the right portion.
- An outer foam enclosure allows operation at low temperature (≤ -40^{o} ?).

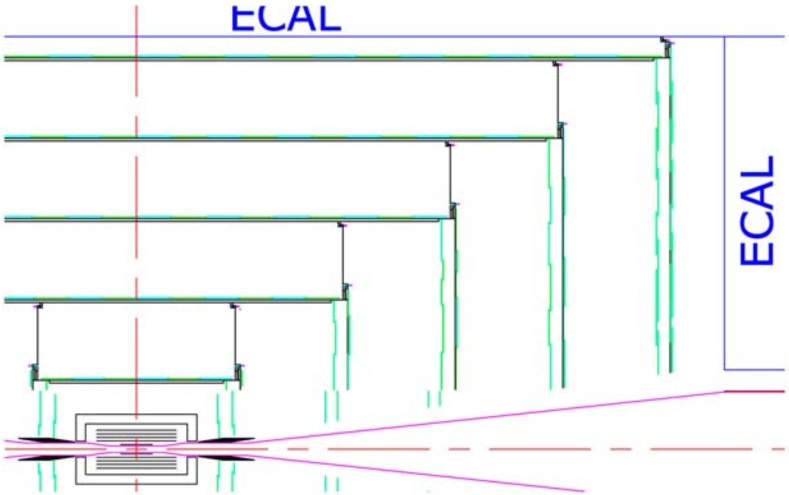


Modifications to Allow Servicing of the Vertex Chamber

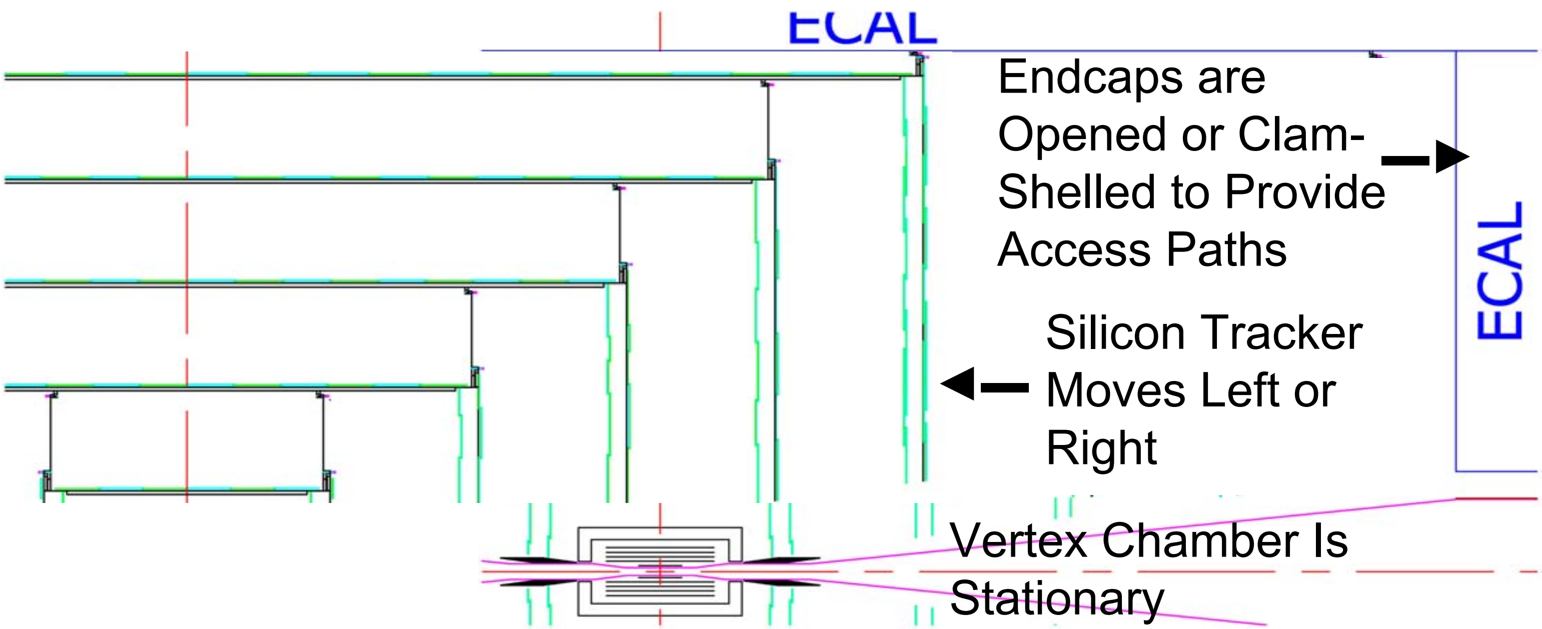
- Requirement: The vertex detector should be accessible for installation and repair without removing beam pipe.
- Disks are separated into an outer radius portion and a smaller radius portion.
  - The smaller radius portion could employ a different technology, such as pixels.
- Disk portions carried by the beam tube assembly are offset in Z to provide overlap with corresponding outer radius disks.



Modifications to Allow Servicing of the Vertex Chamber



Normal "Closed" Positions



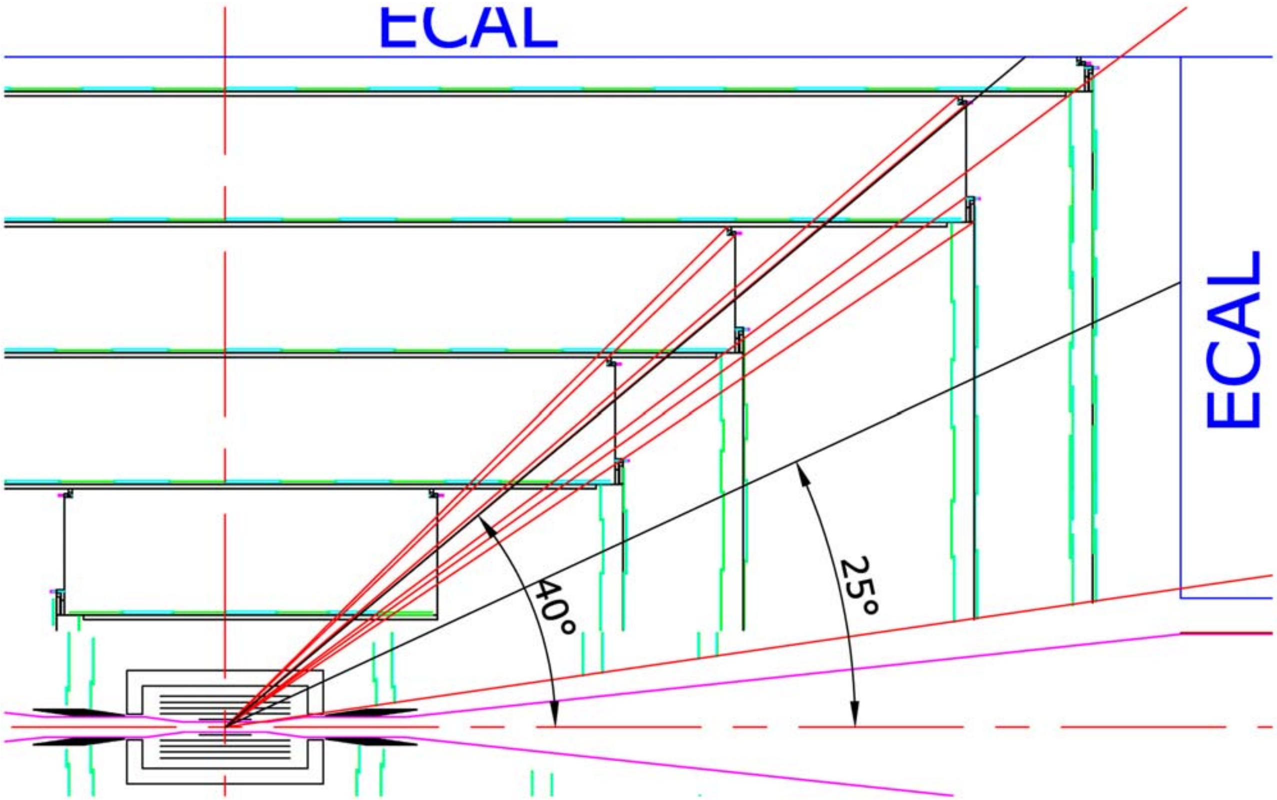
Endcaps are Opened or Clam-Shelled to Provide Access Paths

Silicon Tracker Moves Left or Right

Vertex Chamber Is Stationary

Modifications to Control Projective Geometry

- Note that, in previous transparencies, the barrel-to-barrel and disk mechanical connections are projective. However:
  - CF connecting disks can have spokes rather than being continuous.
  - Ball mounts and spokes need not align in azimuth.
- Projective material could be reduced further by adding one sensor to barrels 1, 2, and 4 (each side of Z = 0), as shown below.

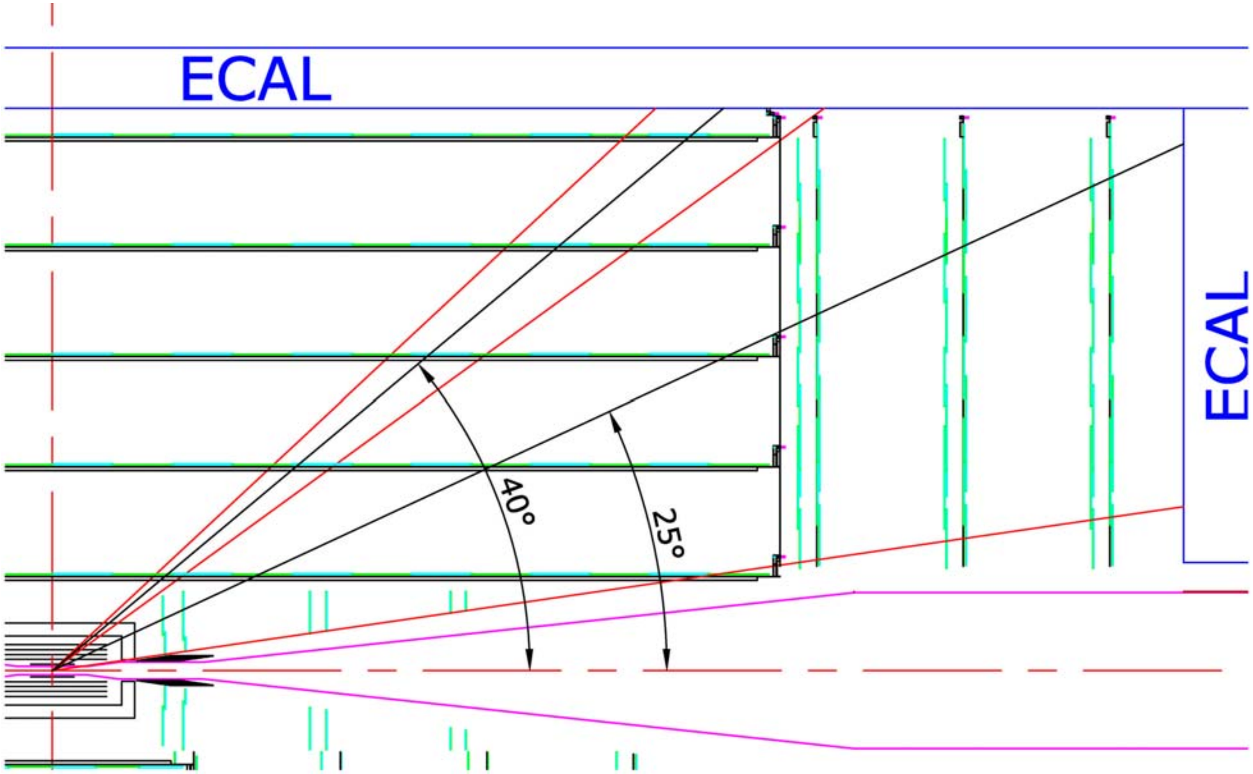


Geometry Choices under Consideration

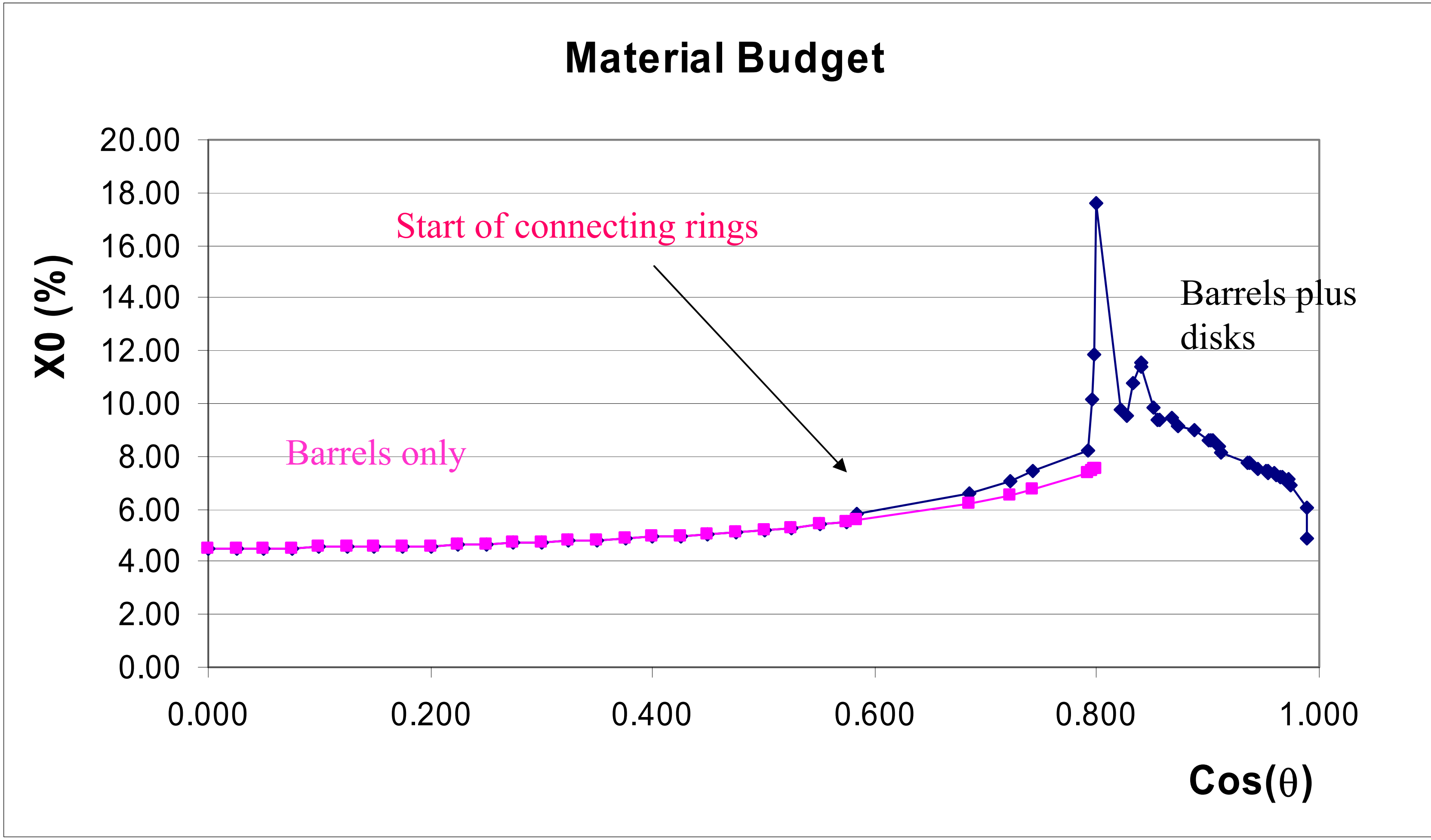
- Number of barrel (disk) layers
  - Adequate momentum resolution is achieved with 5 layers plus the vertex chamber.
  - Does stand alone tracking for decays outside the vertex chamber require more disk and barrel layers?
  - Up to 10 layers have been suggested.
- Number of layers with stereo
  - The Victoria design assumed no stereo in the barrels.
    - Each sensor would be individually read out. Then knowing the sensor in which a hit occurred would provide limited z information.
  - The design assumed ~ 90^{o} degree stereo in the disks.
    - Except at the innermost radii, occupancies are low (a few %).
    - Individual read out of each sensor limits the number of ghosts.
  - Are additional stereo layers needed?
- Should all barrels have the same length?
- More extensive simulation studies are needed to answer these questions.

Long Ladders

- Groups at Santa Cruz and Paris have been interested in long ladders.
  – More consistent with disks at the ends of a barrel region
- S/N with longer readout sections and appropriately designed chips is under investigation.
- Low incidence angles near barrel ends could be an issue.
- Cost may increase if the solenoid needs to be lengthened.



Radiation Lengths for the Victoria Design
(Marcel Demarteau)



- The 'hotspot' at the transition region of barrels / disks might be alleviated by the geometry changes suggested earlier.

Babar Silicon Tracker

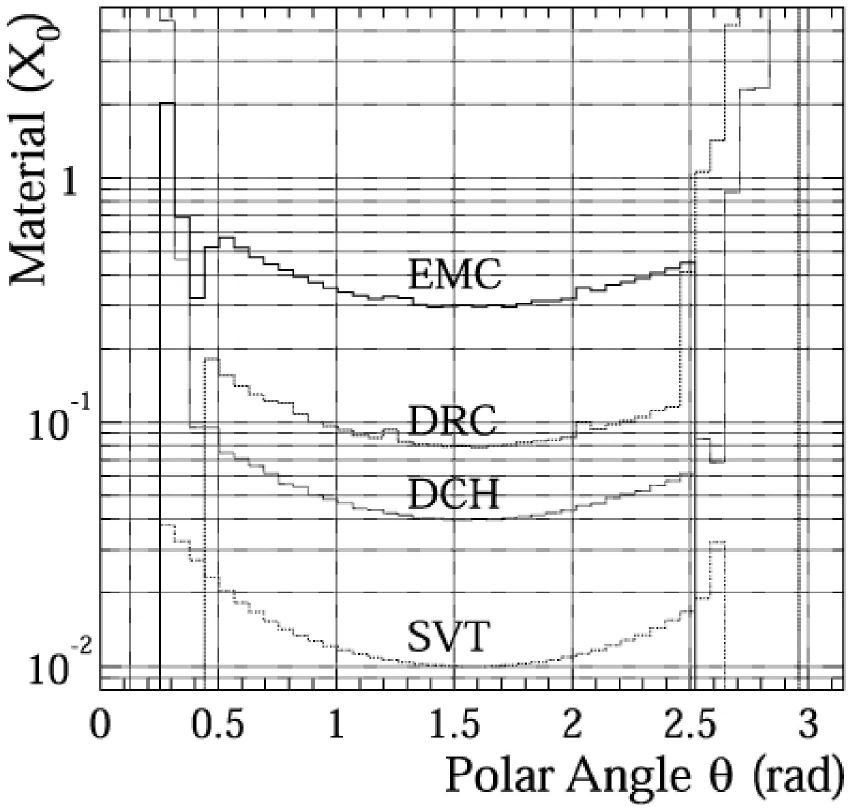
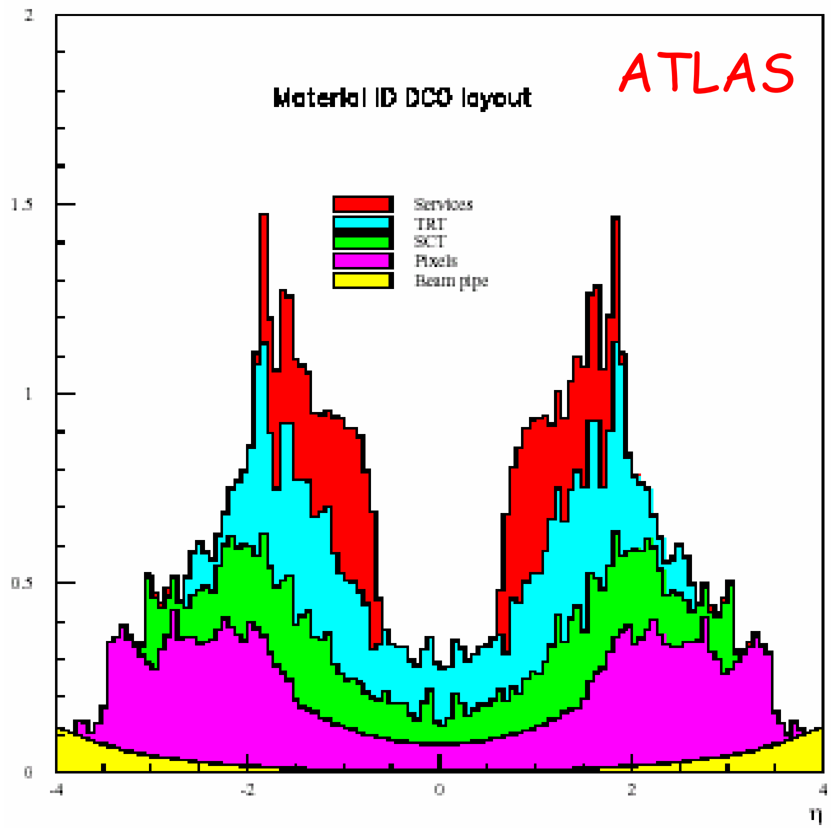
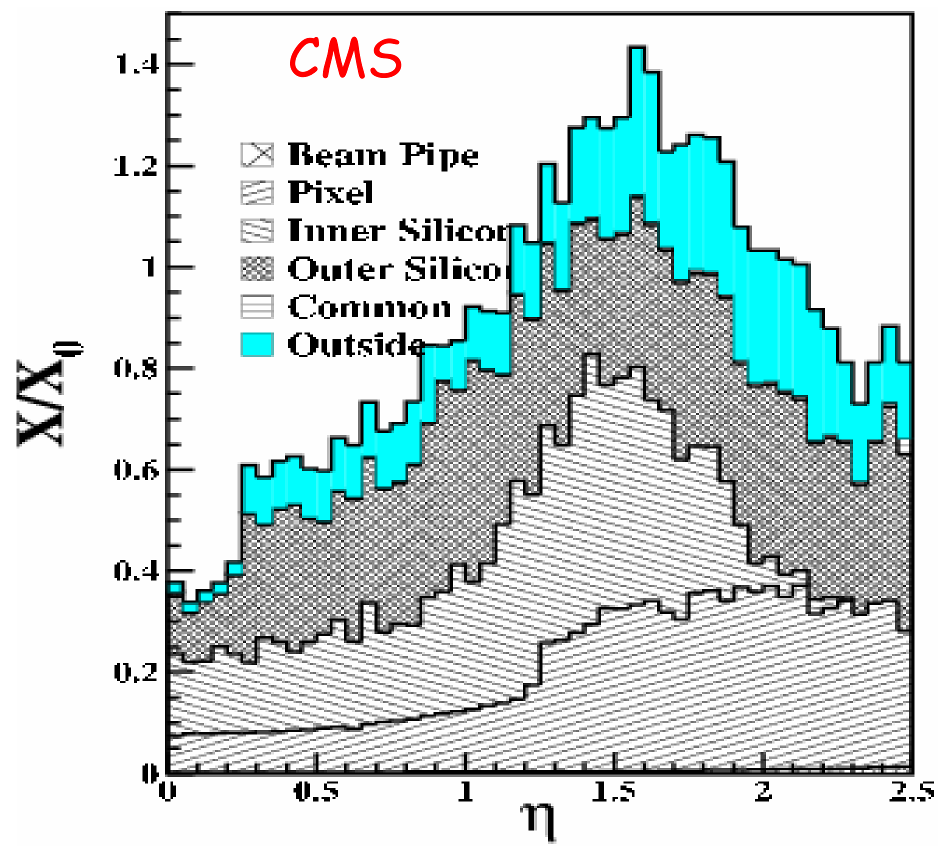


Figure 3. Amount of material (in units of radiation lengths) which a high energy particle, originating from the center of the coordinate system at a polar angle θ, traverses before it reaches the first active element of a specific detector system.

- Babar: 5 layers of double-sided Si
- Stays below 4% at normal incidence traversing SVT; average of 0.8% X_0 per layer
- Ref: The BaBar Detector, NIM A479: 1-116, 2002

For comparison, material budget in LHC experiments



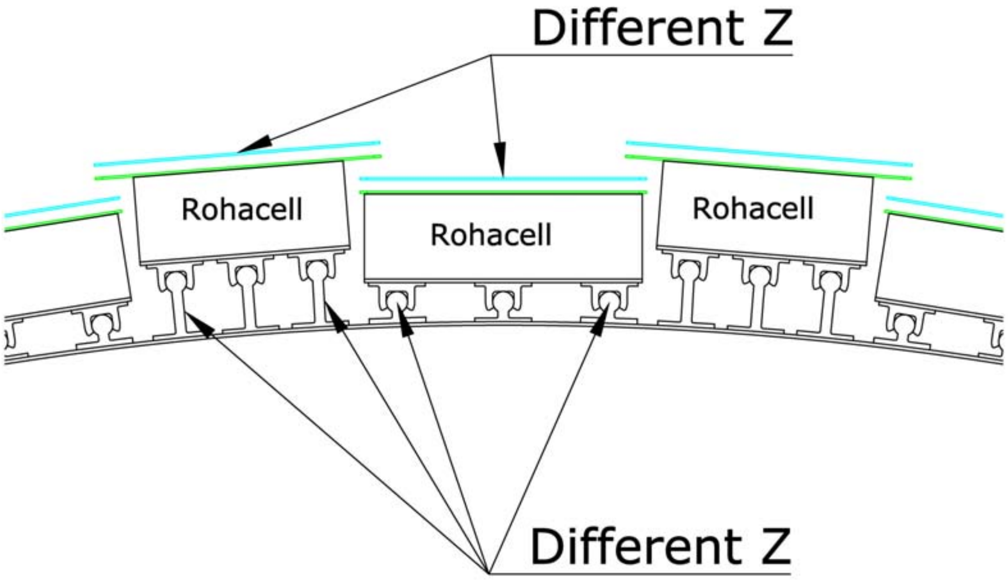


Starts at about 30% X0, including transition radiation tracker

Starts at about 35% X0 (~27% X0 excluding pixel detector)

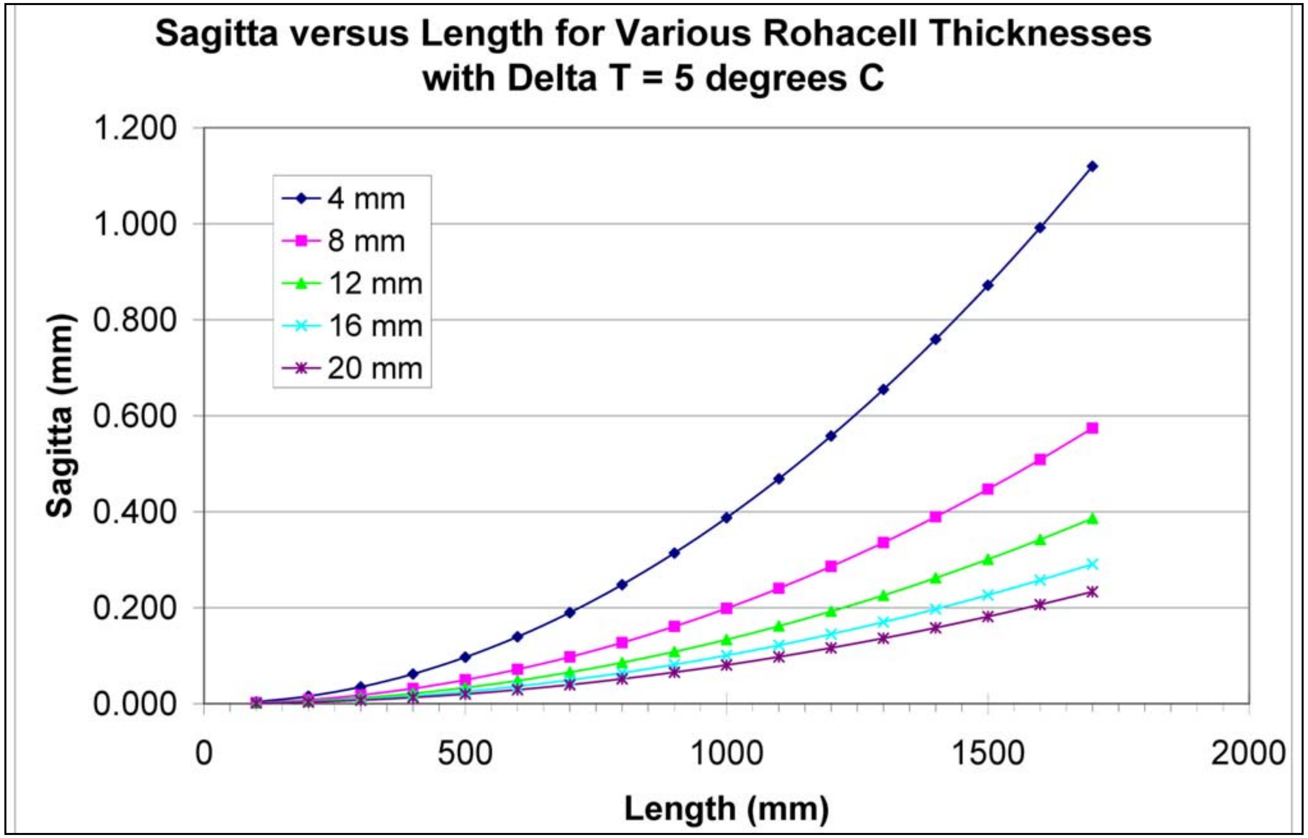
One Approach for Multi-Sensor Ladders

- Sensor – Rohacell – CF Sandwich
- CF and Rohacell would likely be narrower and shorter than the region covered by sensors.
  - That allows overlap in Phi and Z.
- CF (and Rohacell) need not be "solid". Holes could be cut so that a significant fraction of the area covered is free of CF (Rohacell).
- Three point ball and socket mounting (parts and photo from Kurt Krempetz)



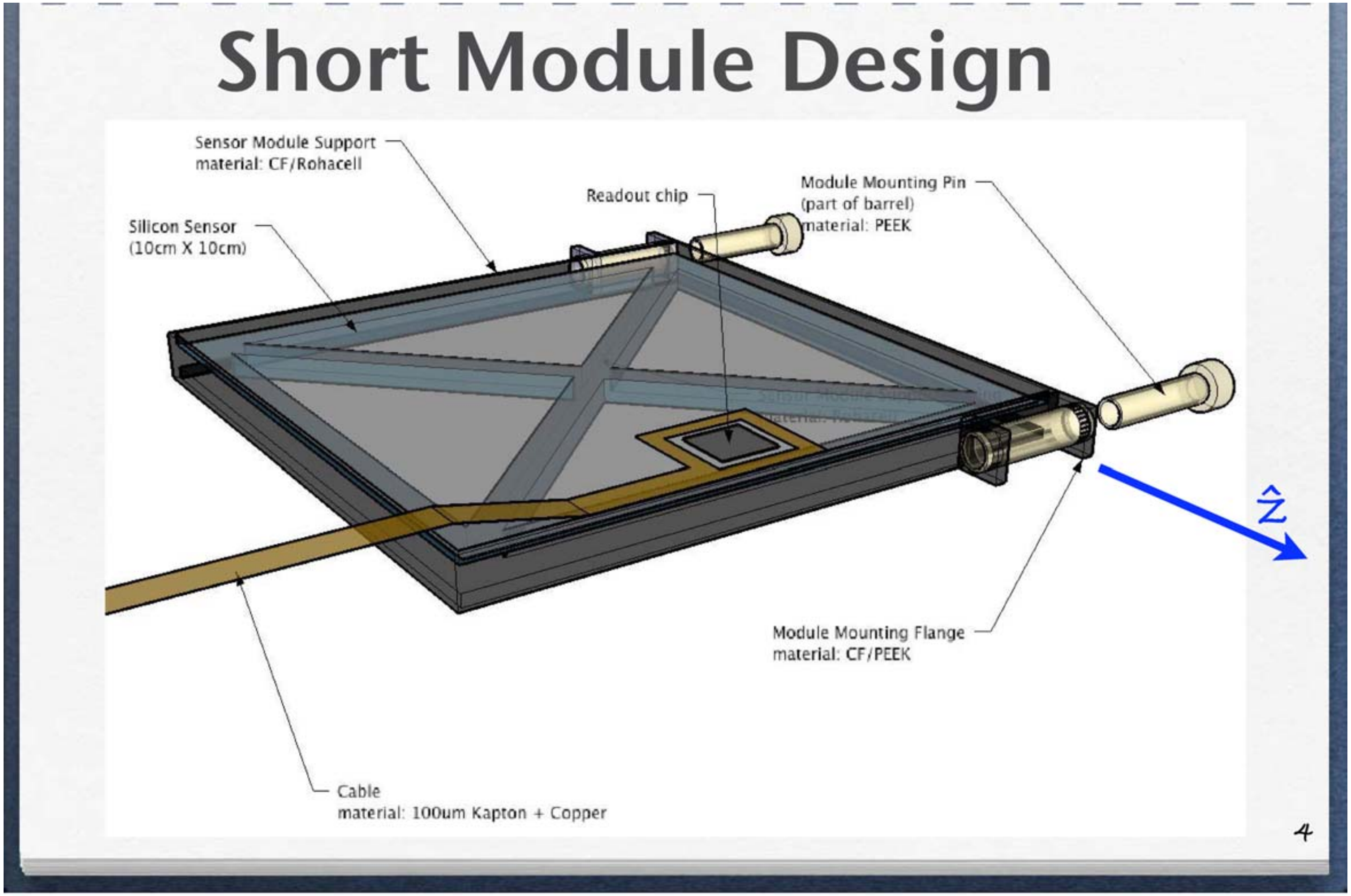
Thermal Bowing

- Thermal bowing as a function of ladder length was estimated based upon zero bending stiffness of sensor and CF (treated as 2-D problem).
  - CTE of silicon was taken to be 2.61×10^{-6} per ^{o}C.
  - CTE of CF was taken to be zero.
- Sagitta = 0.100 mm for dT = 5 ^{o}C, L = 865 mm, and Rohacell thickness = 12 mm



Proposal for Single Sensor Modules, Tim Nelson (SLAC)

- Note the beam direction
- The pigtail connects to a bus cable, which allows natural multiplexing of sensors

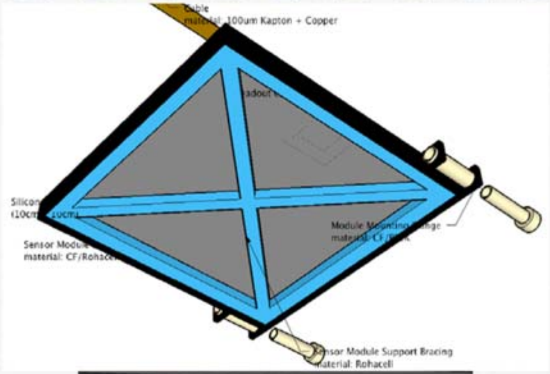


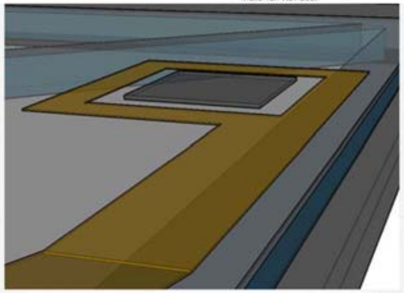
Proposal for Single Sensor Modules, Tim Nelson (SLAC)

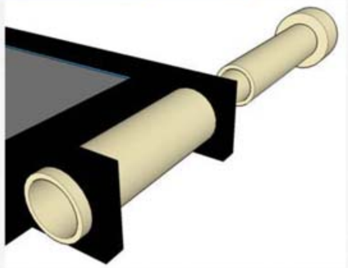
- Sensors are overlapped in azimuth following a spiral geometry
- Lorentz drift is accommodated by the mounting angle

Module Details

- A carbon-fiber/rohacell frame
  - Simple
  - Low mass
  - Easy handling
- Chip, cable bump-bonded to silicon: traces on silicon responsible for all interconnection
  - low mass
  - monolithic assembly
- Mount tangentially to CF support cylinder
  - Easy (one-hand) mounting to cylinders
  - Serviceable after barrel assembly complete







5

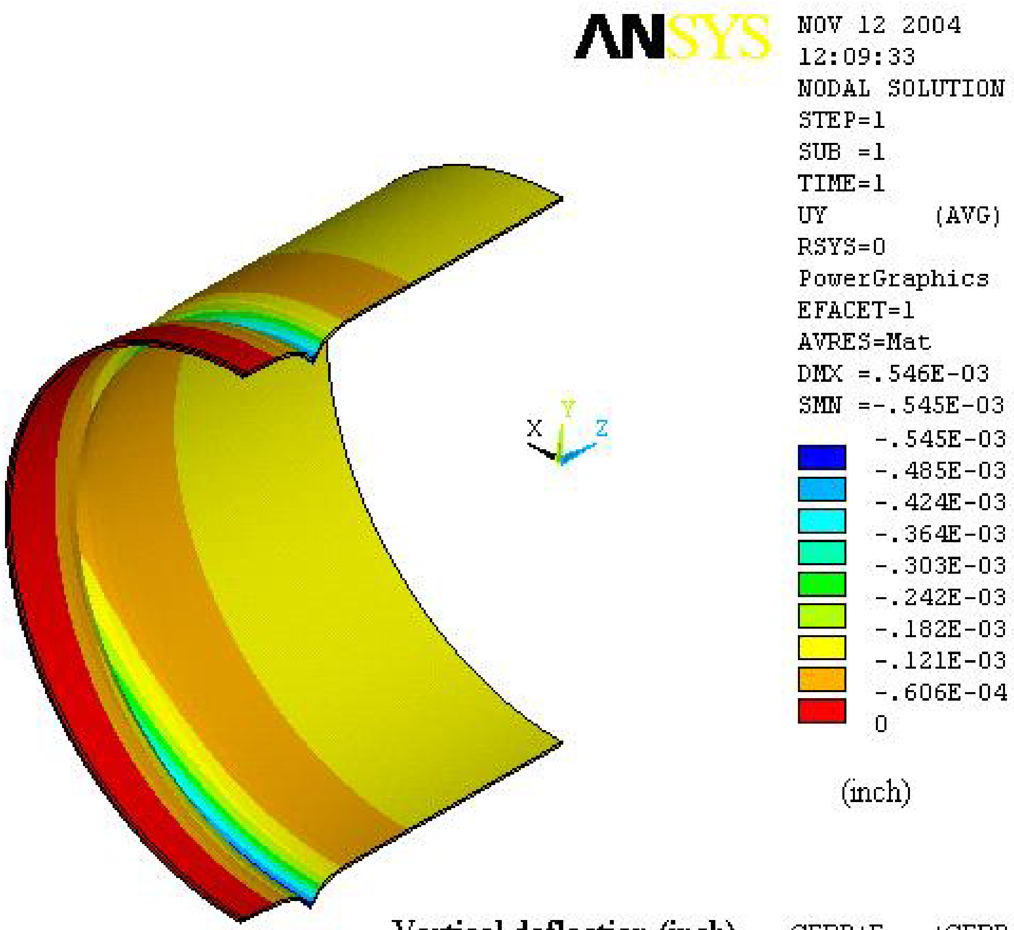
Finite Element Analysis (Kurt Krempetz, Ang Lee)

- Started by modeling Barrel 5 (the largest radius barrel)
  - Outer Radius=1233mm
  - Length=3359mm
- Barrel Wall:

  2 Skins of .25mm Quasi-Isotropic Carbon Fiber lay-up, sandwiched about 13 mm of Rohacell foam
- Unidirectional Carbon Fiber:
  - Modulus=724MPa (105msi)
  - Resin Content RC=40%
    - Gives gives a average Modulus of 165MPa (24msi)
- Rohacell 31 Foam
  - Modulus=34MPa (5msi)
- Two Loads were applied to the Model:
  - Barrel 5 weight including the Silicon on barrel 5
    - Circumferentially and Longitudinally Uniform Load of 44,196g (~97 lb)
  - Barrel's 4-1 weights including silicon and the 4 silicon disks attached to those barrels
    - Circumferentially Uniform Load of 100,600g (~222 lb) Concentrated at Two Z-Locations
- The end of the barrel 5 is held circular
  - Fixed in the radial and tangential directions
  - Represents a limiting case

Finite Element Analysis

- Maximum deflection from a ¼ model = 14 μm.
- Adding end rings reduced that to 7 μm.
- An analysis with more realistic end constraints is in progress.



Vertical deflection (inch)

CFRP+Foam+CFRP
(0.25 mm+13mm+0.25 mm)

In Conclusion

- Steady progress has been made on designs and design constraints.
- Opportunities to contribute exist in many areas, some of them coupled.
  - Simulation
    - Optimization of barrel and disk numbers, lengths, and locations
    - Tracking with and without the use of the vertex chamber
    - General tracking algorithms
    - Effects of material
  - Module design
    - Long versus short modules
    - Stereo angles
  - Readout
    - Chip design
    - Cables from chips to ends of barrels / peripheries of disks
    - Optical connections from those locations to the outside world
  - Overall support
    - Mechanical analysis
    - Assembly techniques and prototyping
    - Measurements of sensor positions
    - Provisions for servicing
  - Test beams (organized by Jae Yu)
- FNAL efforts are design oriented. All volunteers are welcome.